Radiometric Balloon-Flight Results from the HySICS

CLARREO Science Definition Team Meeting

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HyperSpectral Imager for Climate Science

HySICS is an instrument intended to acquire extremely accurate radiometric images of the Earth relative to incident sunlight

Ratio of solar incoming to outgoing radiances benchmarks climate without reliance on accuracy

HySICS is a balloon payload that is mounted on the Wallops Arc Second Pointer (WASP) flying out of Ft. Sumner, NM

Questions to be answered:
Climate data benchmark technique demonstration

Flights: Sept. 29, 2013 and 18 Aug. 2014
Observations: 8 hours at float

Principal Investigator: *Greg Kopp*

HyperSpectral Imager for Climate Science

PI: Greg Kopp / LASP

Objective

Build and flight test a hyperspectral imager with improved radiometric accuracies for climate science
- 350-2300 nm with single FPA to reduce cost & mass
- <0.2% (k=1) radiometric accuracy
- <8 nm spectral resolution
- 0.5 km (from LEO) IFOV and >100 km FOV
- <0.13% (k=1) instrumental polarization sensitivity

Perform two high-altitude balloon flights to demonstrate solar cross-calibration approach and to acquire sample Earth and lunar radiances

HySICS to demonstrate climate science radiometric accuracies in shortwave spectral region

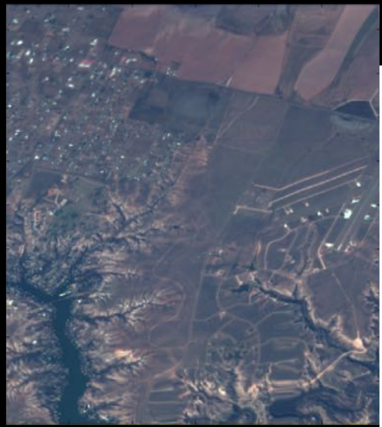
Approach

Single HgCdTe FPA covers full shortwave spectral range with reduced mass, cost, volume, and complexity

Incorporate solar cross-calibration approaches demonstrated on prior IIP to provide on-orbit radiometric accuracy and stability tracking

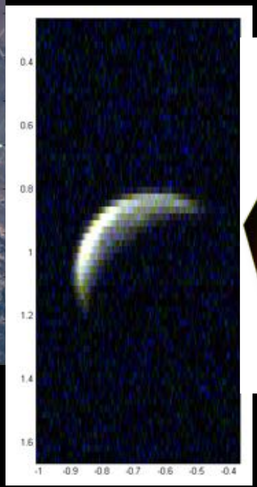
Orthogonal configuration reduces polarization sensitivity

No-cost balloon flights from experienced team at NASA WFF demonstrate on-orbit capabilities

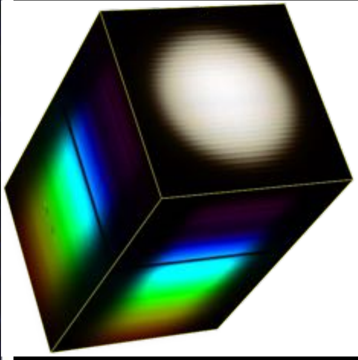


Ground Reconstruction

Lunar Reconstruction

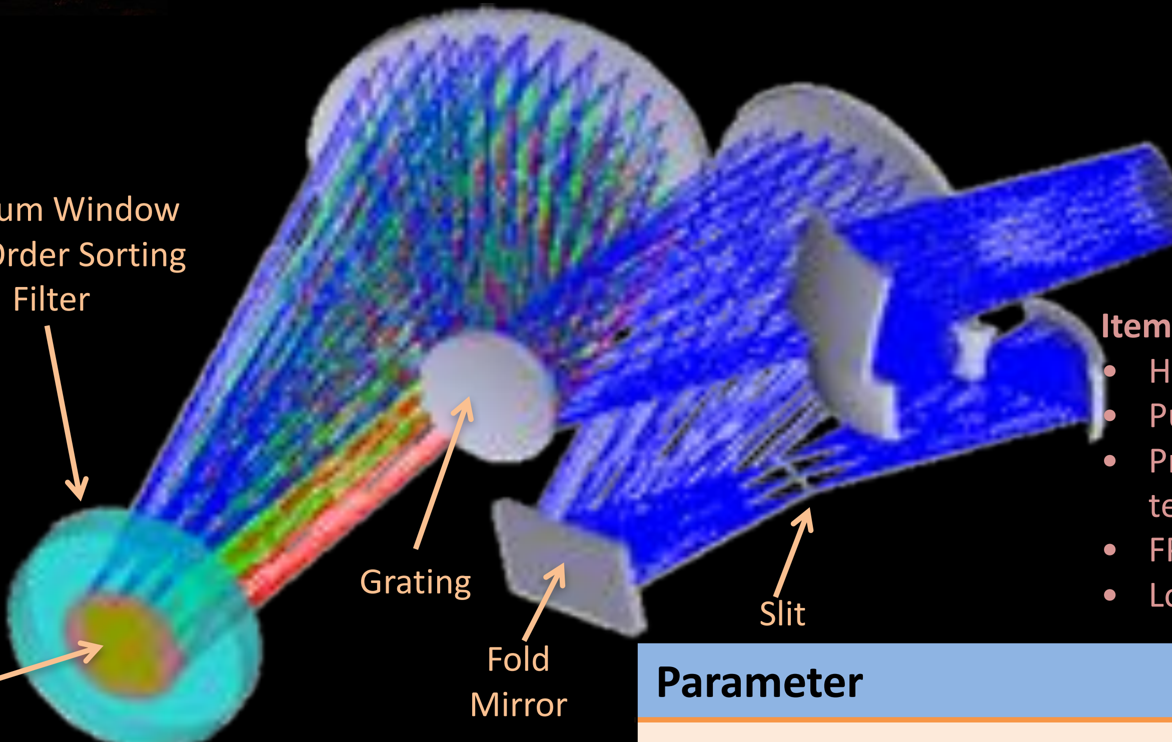


Solar Data Cube



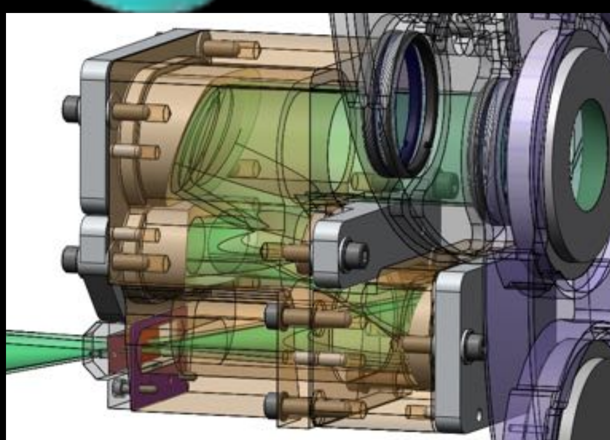
CoIs: Co-I – Peter Pilewskie / LASP
Balloon Flight Manager – David Stuchlik / WFF

HySICS Instrument Optics



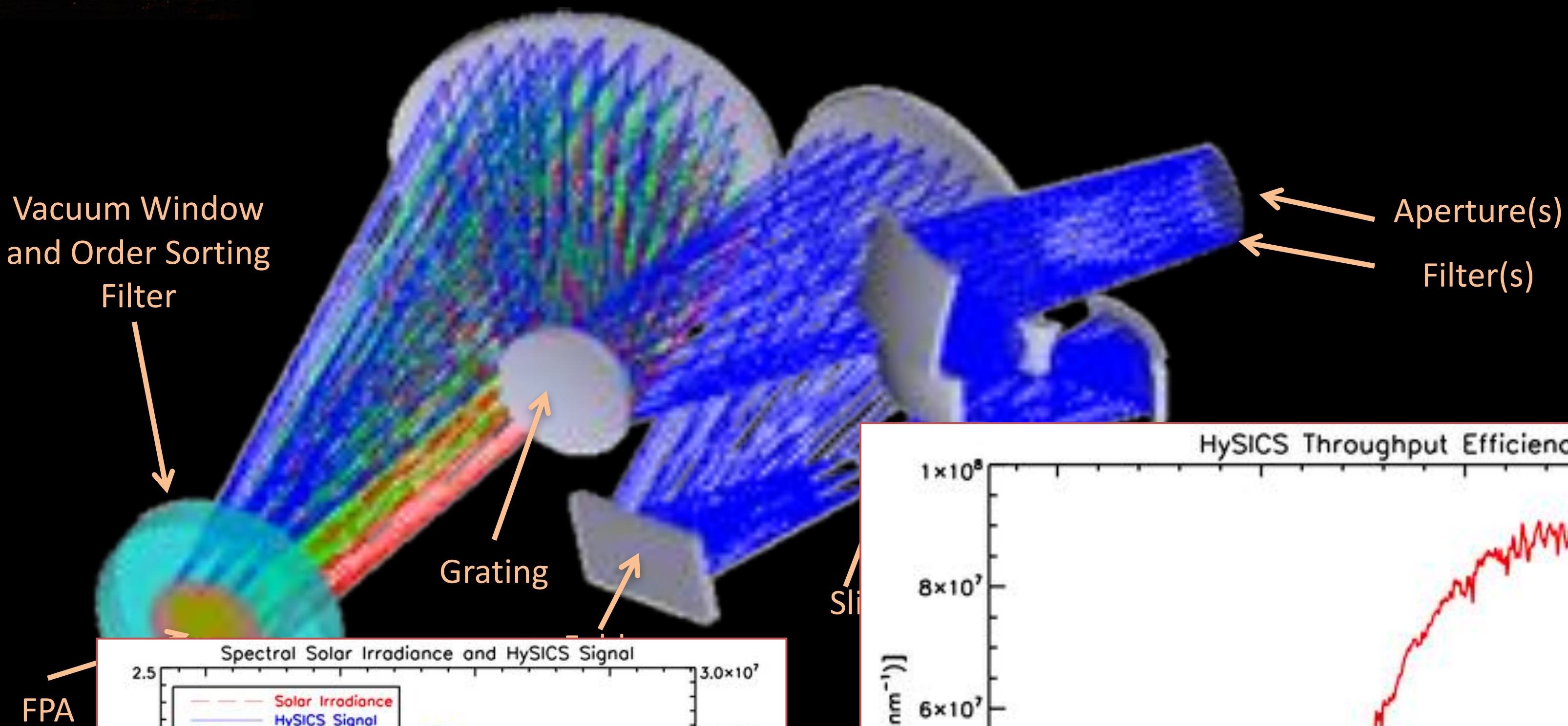
Items Guiding Design:

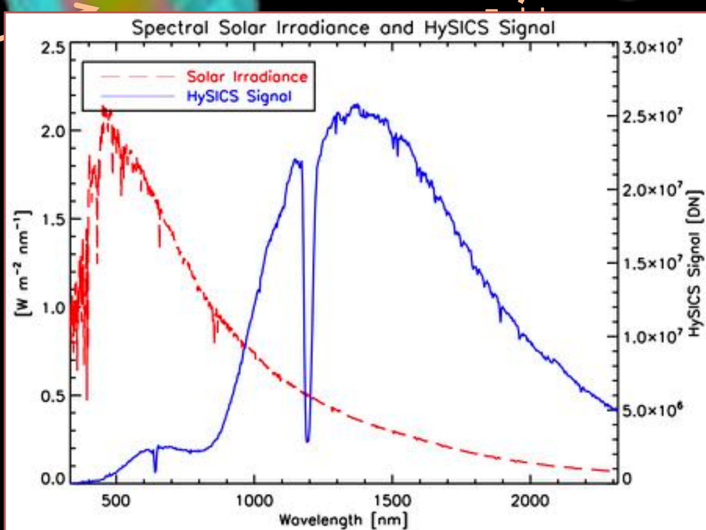
- High altitude balloon flight environment
- Pushbroom imaging spectrometer
- Precision aperture stop in front of the telescope
- FPA operates at 150 K
- Low polarization sensitivity

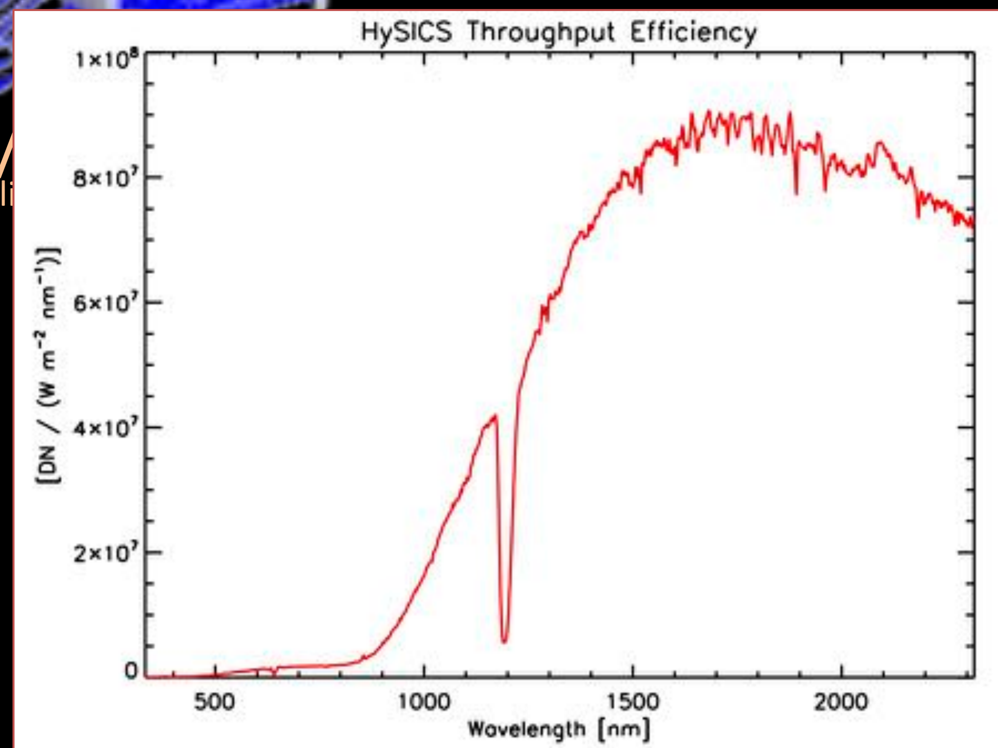


Parameter	Design Requirement
Spatial Resolution	2.5 arcmin
Field of View (cross track)	10°
IFOV	0.02°
Wavelength Range	350-2300 nm
Wavelength Resolution	6 nm, constant, Nyquist
Aperture	0.5, 10, 20 mm diameter

Radiometric Efficiency Calibrated On-Orbit

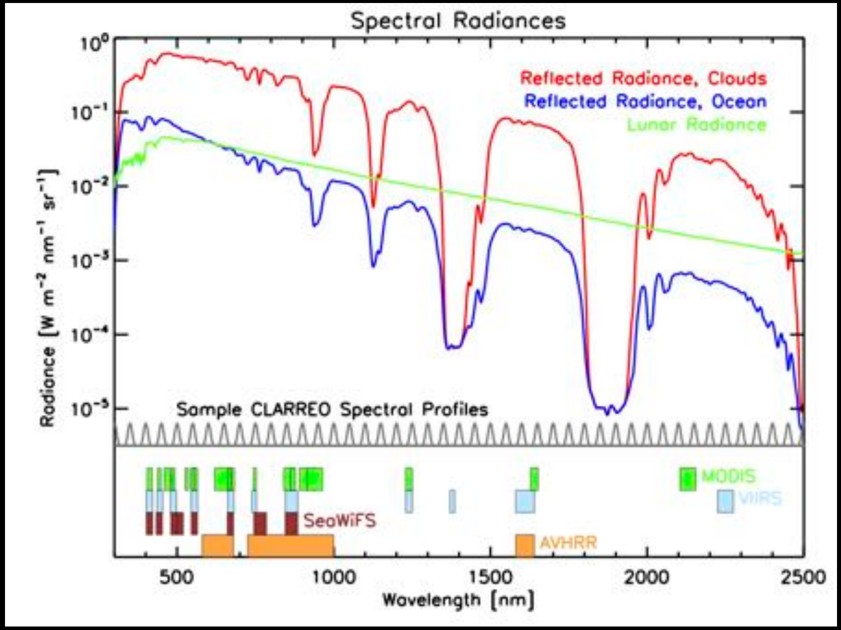






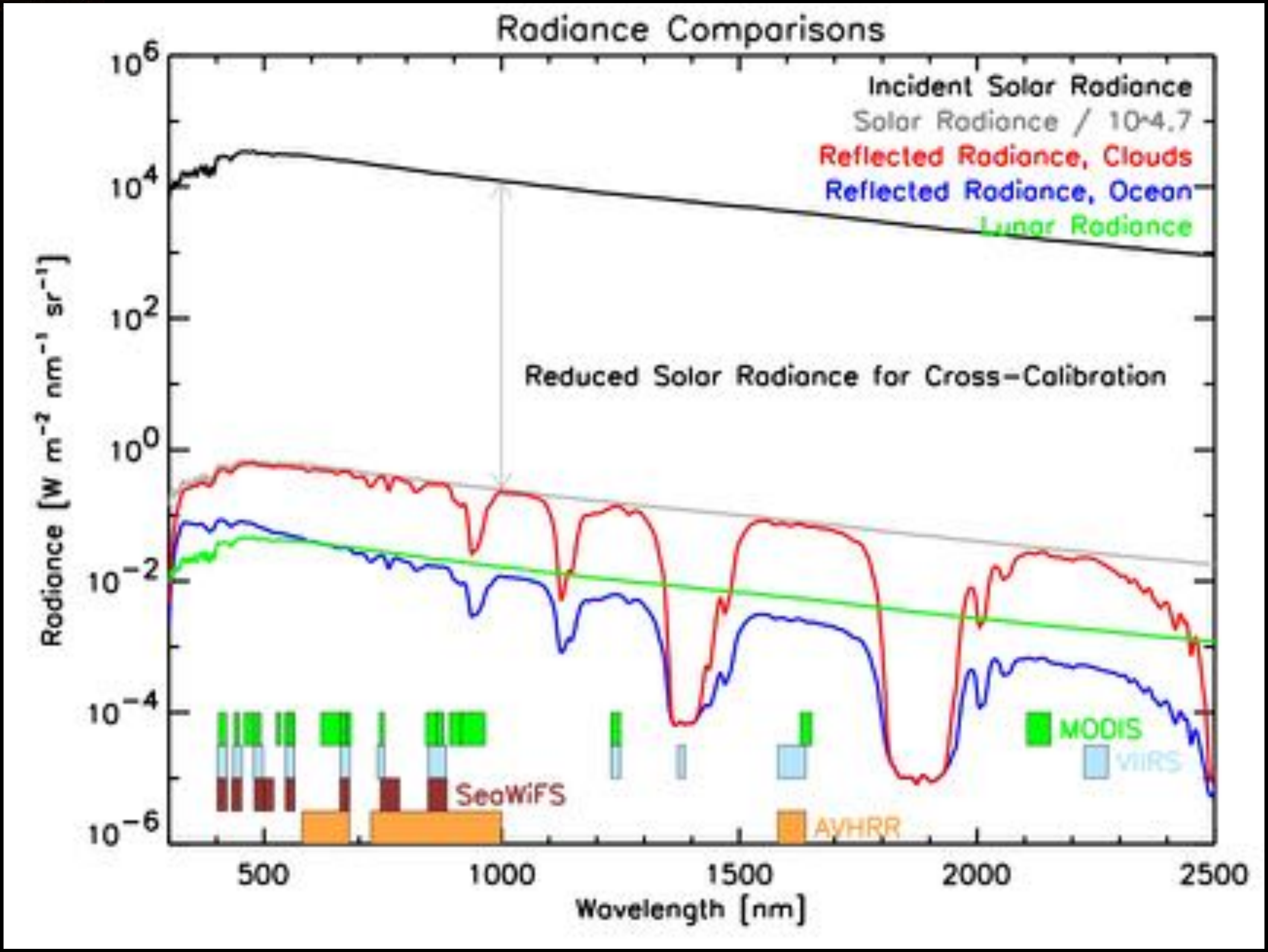
Improve Radiometric Accuracies in Visible/NIR

- Current instruments have >2% radiometric accuracy
  - Accuracy and stability rely on ground calibrations, on-board lamps, cross-calibrations, solar diffusers, or lunar observations



Methods/Type of Calibration	Uncertainties	Constraints
Artificial Test Sites Absolute	• Actual: 3.5% reflectance-based, 2.8% radiance-based • Expected: 2.8% and 1.8%	• Requires ground instrumentation • Requires good atmospheric conditions • Requires specific sensor operations
Stable Deserts Stability	• Actual: 3% • Expected: 1% with BRDF (bandpass dependent)	• Requires non-cloudy images • Requires specific sensor operations
The Moon Stability	• Expected: <1%	• Dynamic range is limited • Req. specific operations & viewing
The Moon Absolute	• Actual: 5-10% • Expected: 1%	• Dynamic range is limited • Req. specific operations & viewing • Requires low uncertainty calibration and radiometric verification of the moon

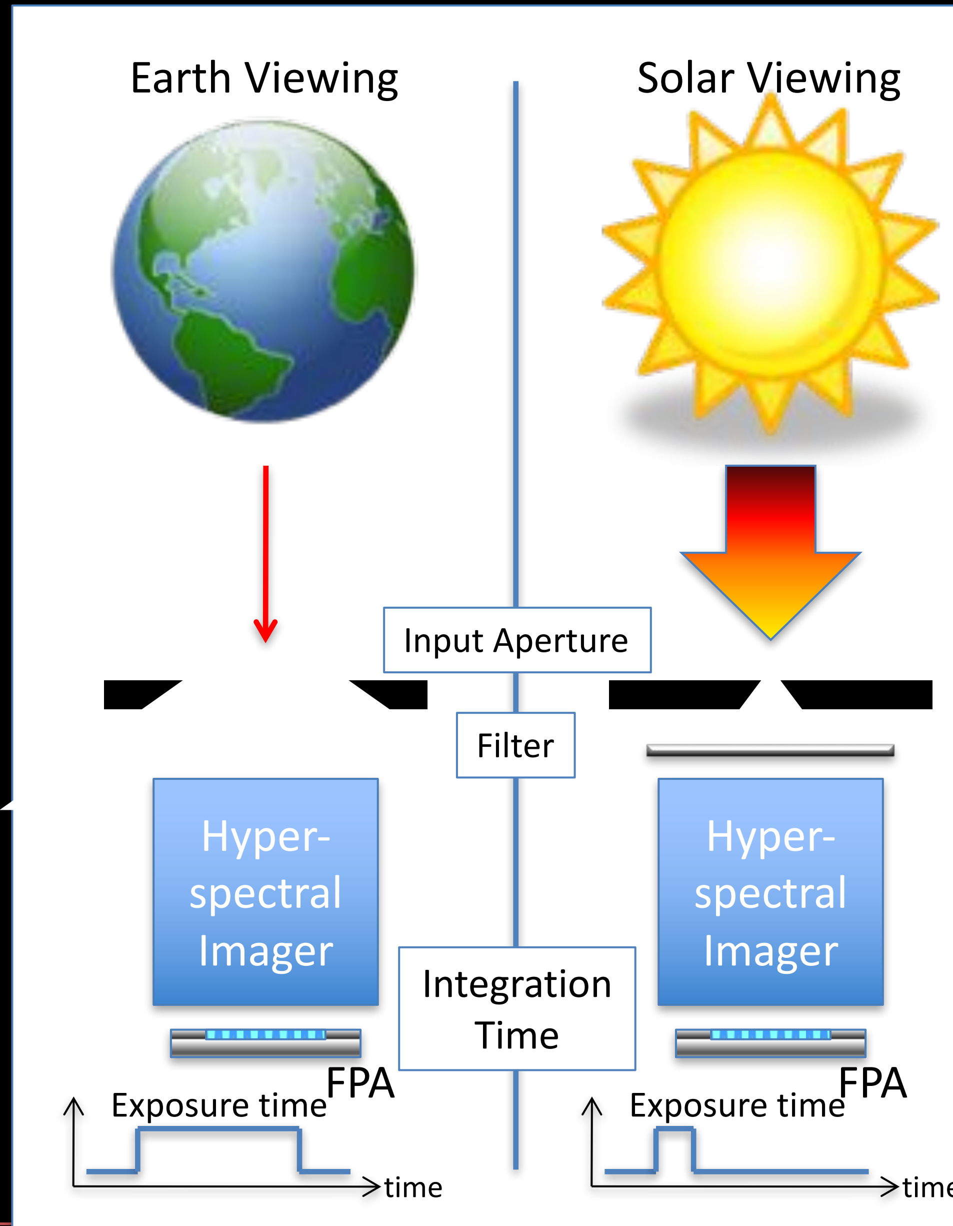
Solar Cross-Calibrations Require ~10^{-5} Attenuation



Attenuation Methods Utilized by HySICS

- **Aperture attenuation** – Reduction of input light-collecting area
  - Can achieve attenuations ~10^{-3}
  - Limited by diffraction
- **Integration-time attenuation** – Reduction of light-collecting time
  - Can achieve attenuations ~10^{-3}
  - Limited by linearity
- **Filter attenuation** – spectral filters calibrated with on-orbit lunar views
  - Can achieve attenuations 10^{-1}
  - Limited by S/N

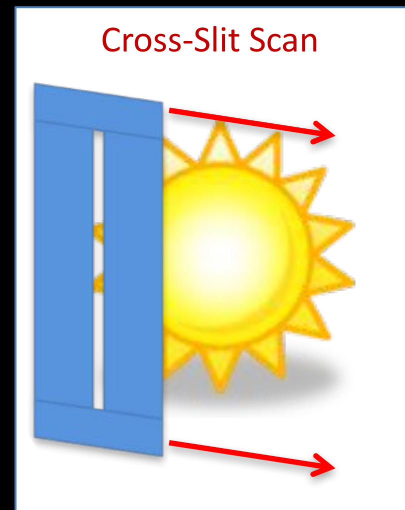
All attenuation methods are <u>relative</u> measurements; direct measurements of solar or Earth irradiances not required.

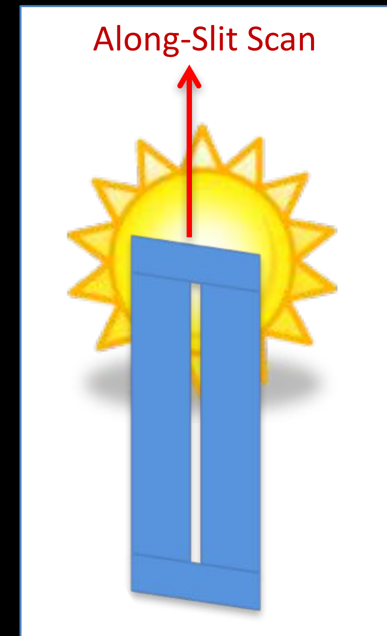


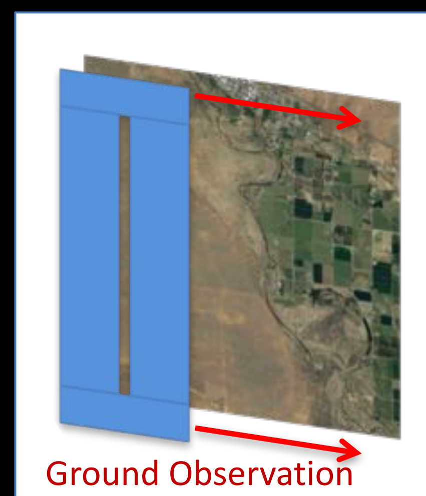
Science and Calibration Observations

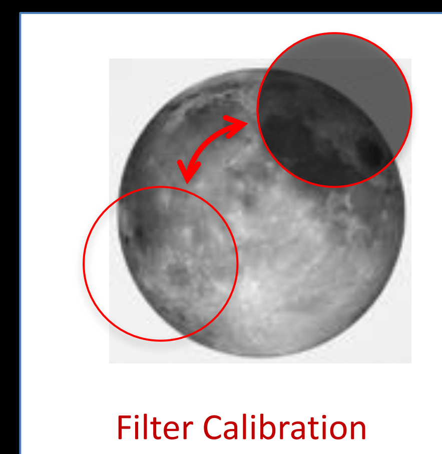
- Ground Observation
  - Acquire hyperspectral data from ground scenes
- Solar Irradiance Measurement (Cross-Slit Scan)
  - Measure spectral solar irradiance by integrating images after cross-slit scan of solar disk
- Flat-Field Calibration (Along-Slit Scan)
  - Scan slit smoothly along diameter of solar disk
  - Requires pointing accuracy of ~15 arcsec
- Calibrations using Moon
  - Filters: Place slit across Moon and acquire measurements with and without filters
  - Flat-field: along-slit scan using large aperture
    - *Drives yet more stringent pointing requirements*

Observations not possible through variable atmosphere, so need >30,000 m altitude



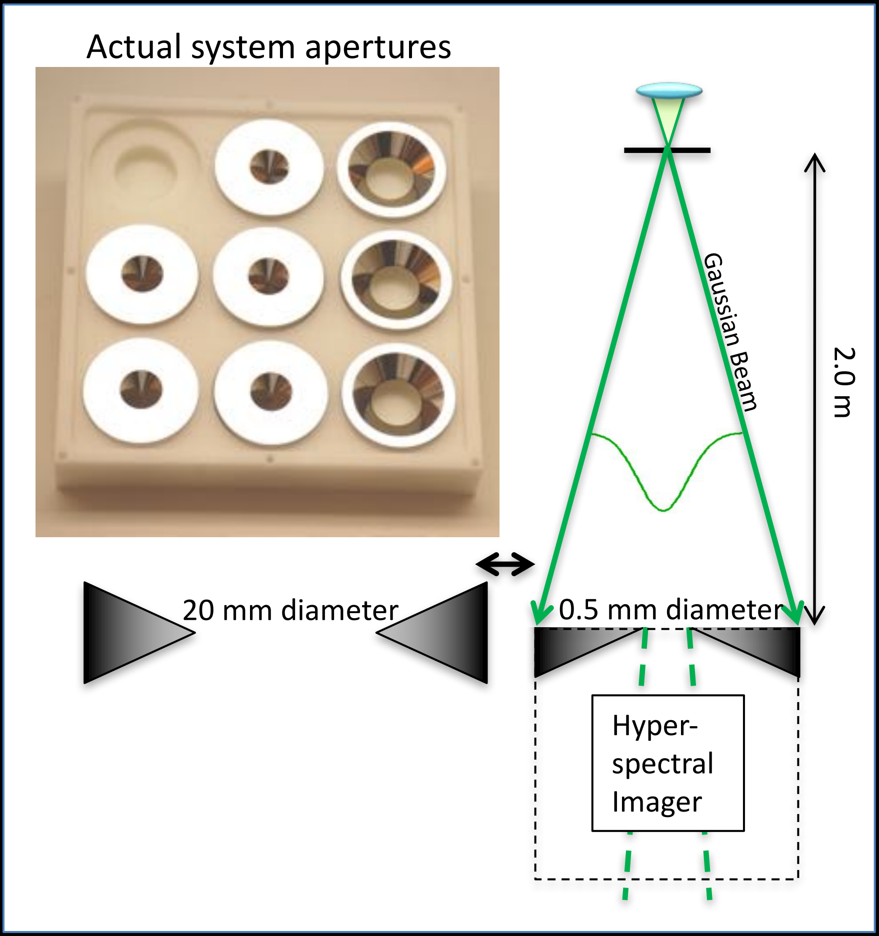






Attenuation Calibrations – Apertures

- NIST-calibrated areas provide uncertainties <320 ppm

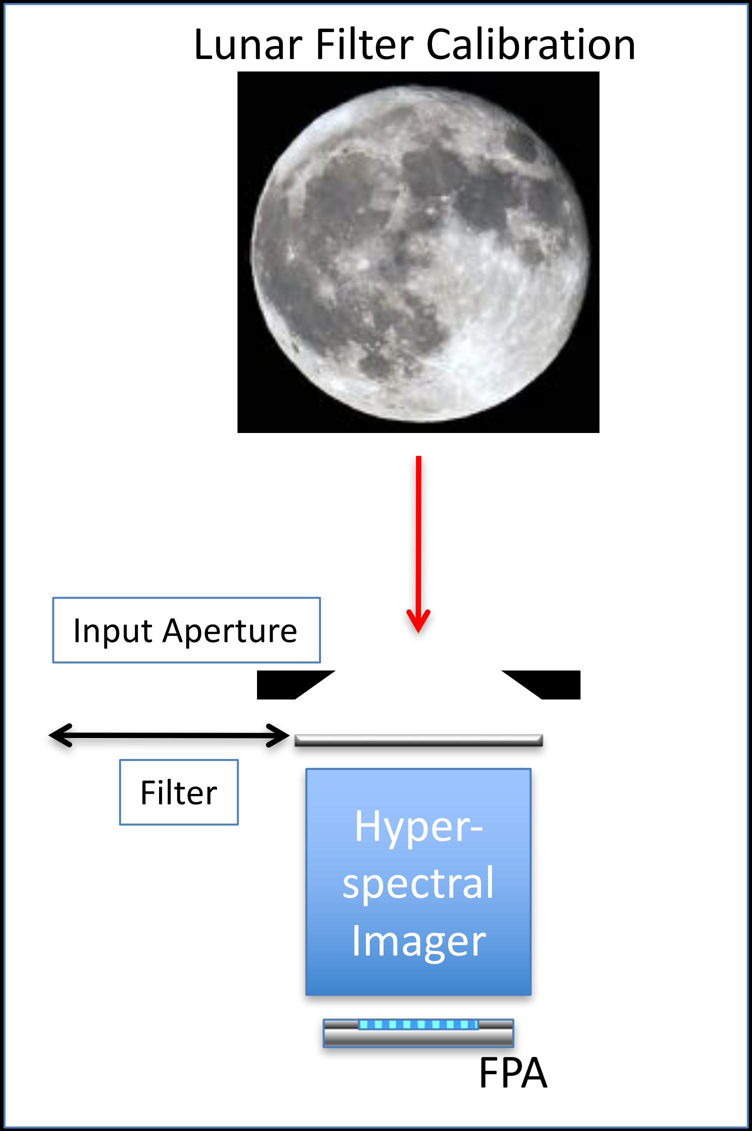


Aperture Diameter (mm)	Aperture Area (mm^2)	Area Uncertainty (ppm) (k=1)
19.9862	313.72454	18
0.51542	0.20865	317

But there's a lot more to it...

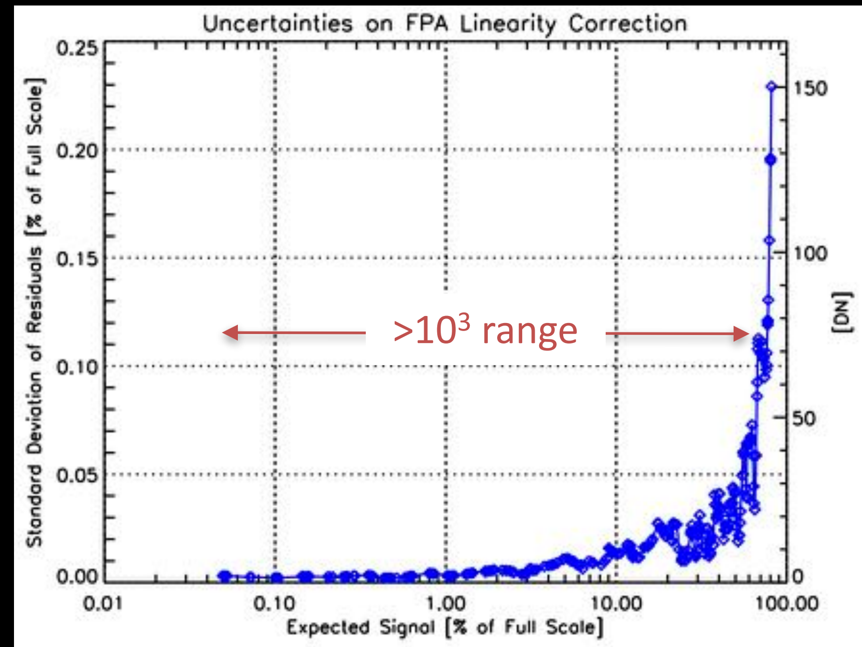
Attenuation Calibrations – Filters

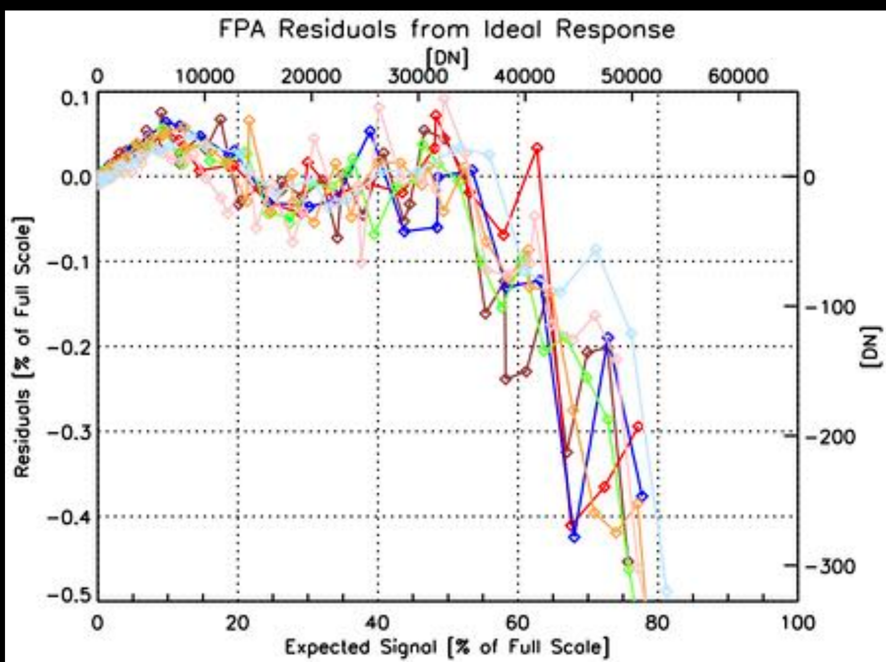
- **Intended attenuations of $10^{-0.9}$**
- Lunar on-orbit relative calibration
  - Succession of filter in/filter out radiance measurements
  - Track possible degradation
  - Low light level (compared to solar irradiance) limits attenuations to $\sim 10^{-1}$
- Absorptive glass filters span spectrum
  - Bulk effect is more stable than thin film
  - Lower reflected light
  - Simpler dependence on angle of incidence



Attenuation Calibrations – Integration Time

- FPA system non-linearity
  - Non-linearities are characterized for attenuations of 10^{-3}
- FPE non-linearity
  - 1 ppm over attenuations of $10^{-3.3}$





FPA linearity greatly exceeded expectations

Obviates need for filters

HySICS Integrated and Ready for Launch

Balloon Inflation

HySICS Launch

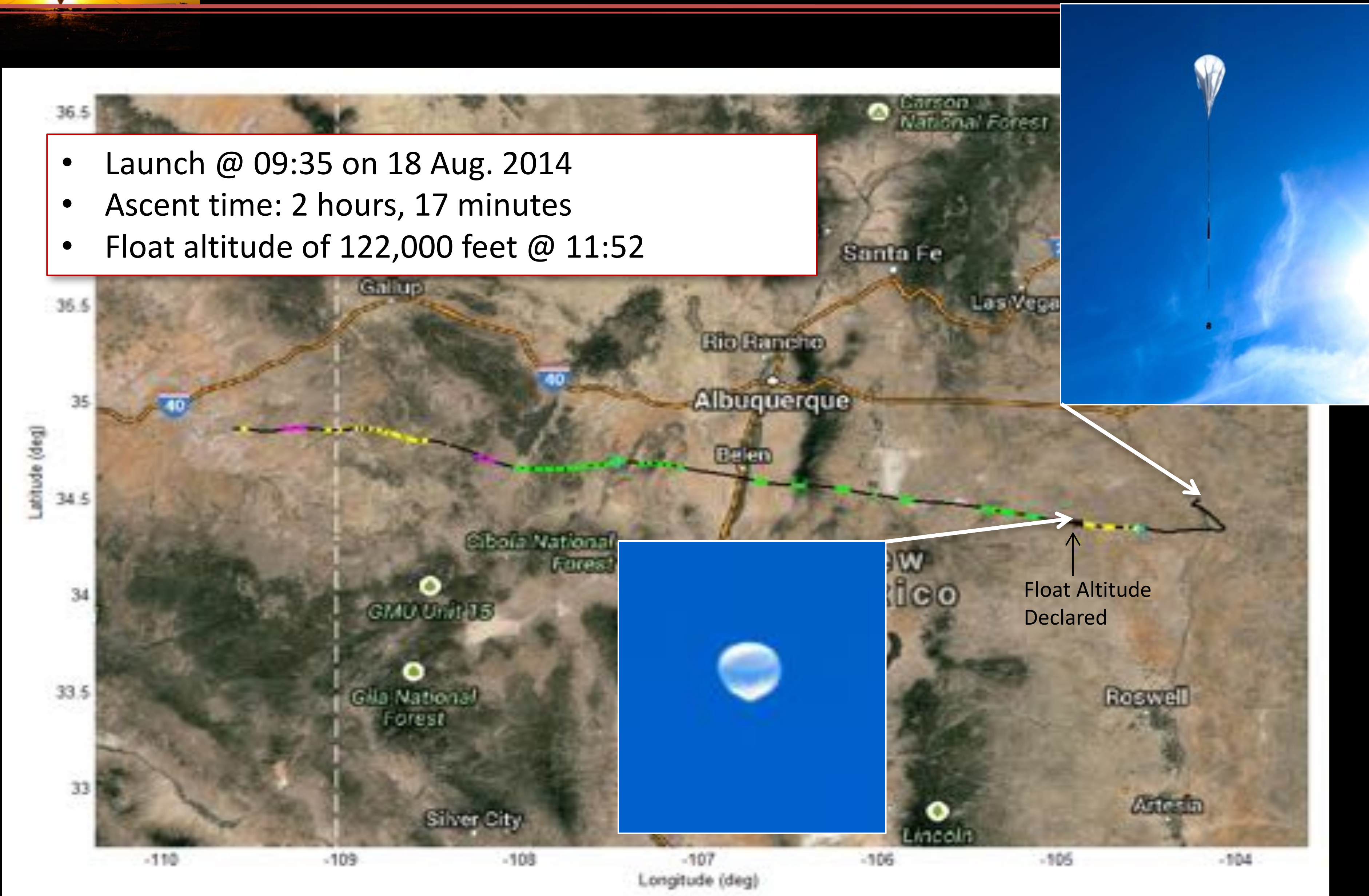
put short HySICS Launch video here

HySICS Flight #2 Summary

- FLIGHT NO.: 650N
- LAUNCH DATE/TIME: August 18, 2014, 15:36 Z
- LAUNCH SITE: Fort Sumner, NM
- BALLOON VOLUME: 0.8 MCM (29.47 MCF)
- BALLOON WEIGHT: 1,675 KGS (3,693 LBS)
- EXPERIMENT WEIGHT: 1,925 KGS (4,244 LBS)
- SUSPENDED WEIGHT: 2,722 KGS (6,000 LBS)
- GROSS INFLATION: 4,836 KGS (10,662 LBS)
- FLOAT ALTITUDE: 37.19 KM (122 KFT)
- BALLOON THICKNESS: 20.32 MICRONS (0.80 MIL)
- SERIAL NO.: 90 / CSBF NO. 1205
- DISCIPLINE: WU / Solar and Heliospheric
- TOTAL FLIGHT TIME: 8 hrs, 54 min

HysICS Flight #2 Path

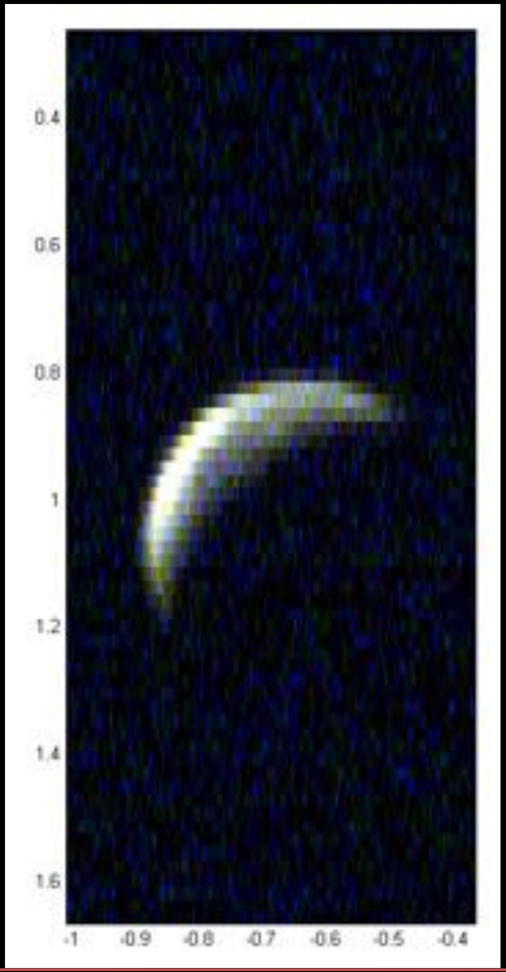
- Launch @ 09:35 on 18 Aug. 2014
- Ascent time: 2 hours, 17 minutes
- Float altitude of 122,000 feet @ 11:52



HySICS Images from Flight #1

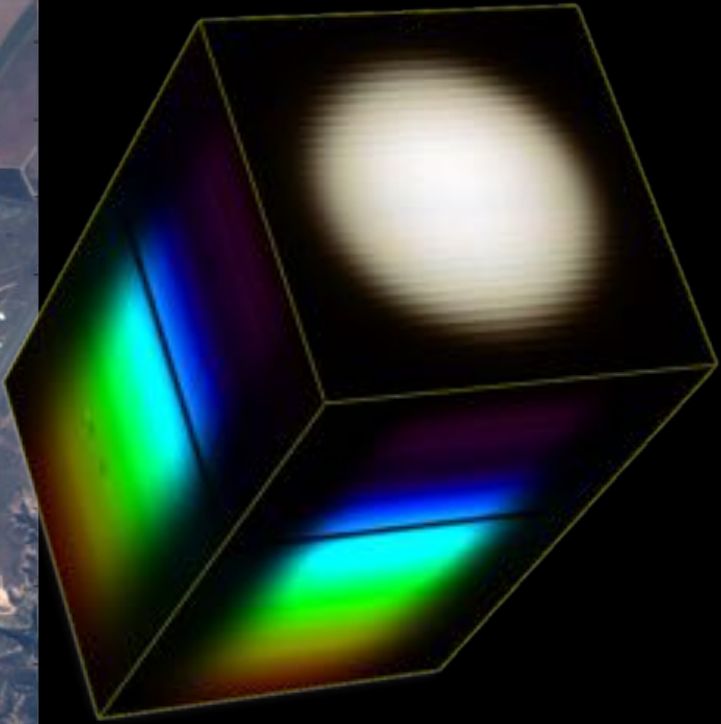
- Flight #1 (Engineering Flight) demonstrated spatial/spectral scanning capability of all three targets

Lunar Reconstruction

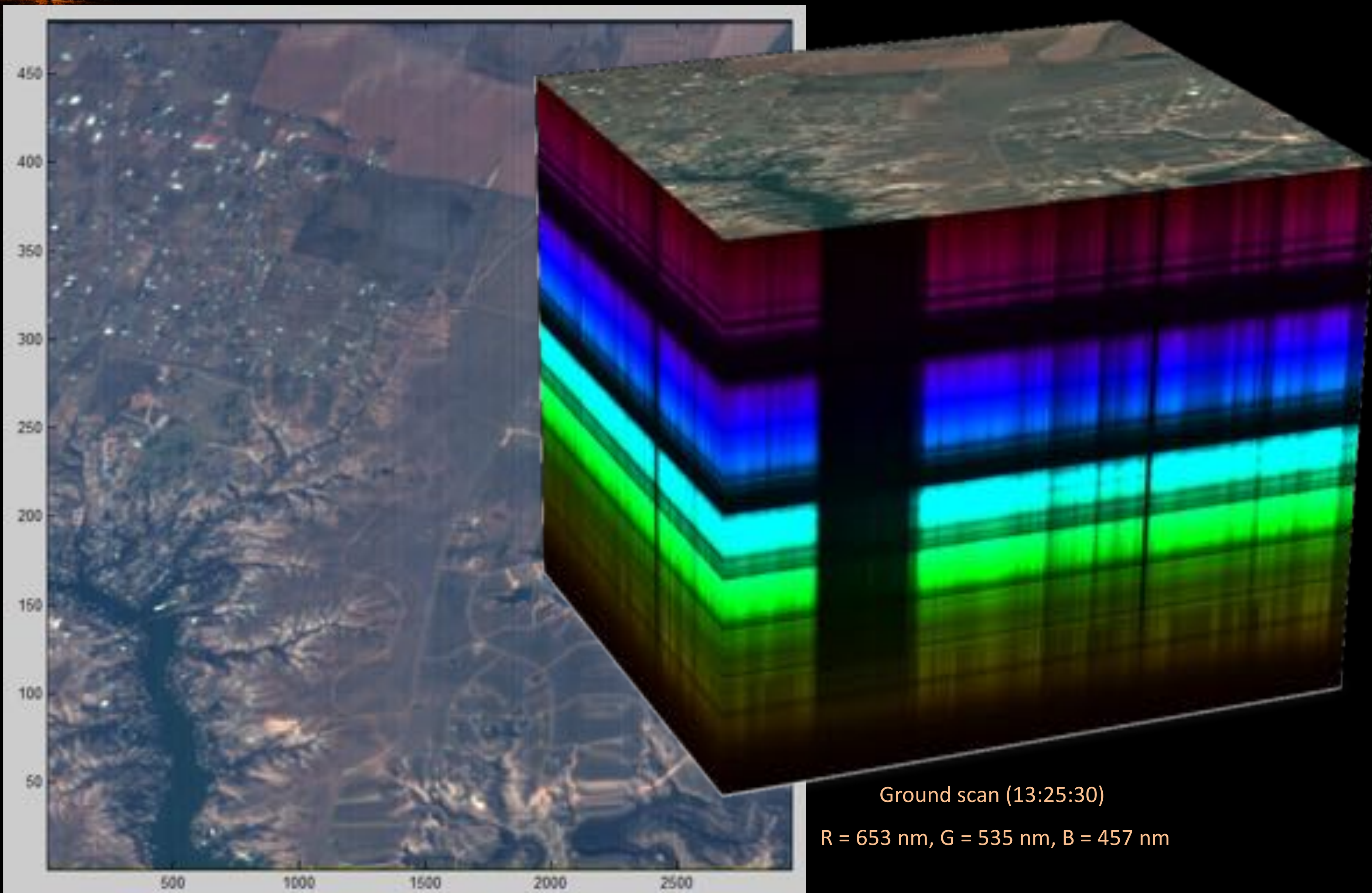


Ground Reconstruction

Solar Data Cube



Ground Scan and Data Cube from Flight #1

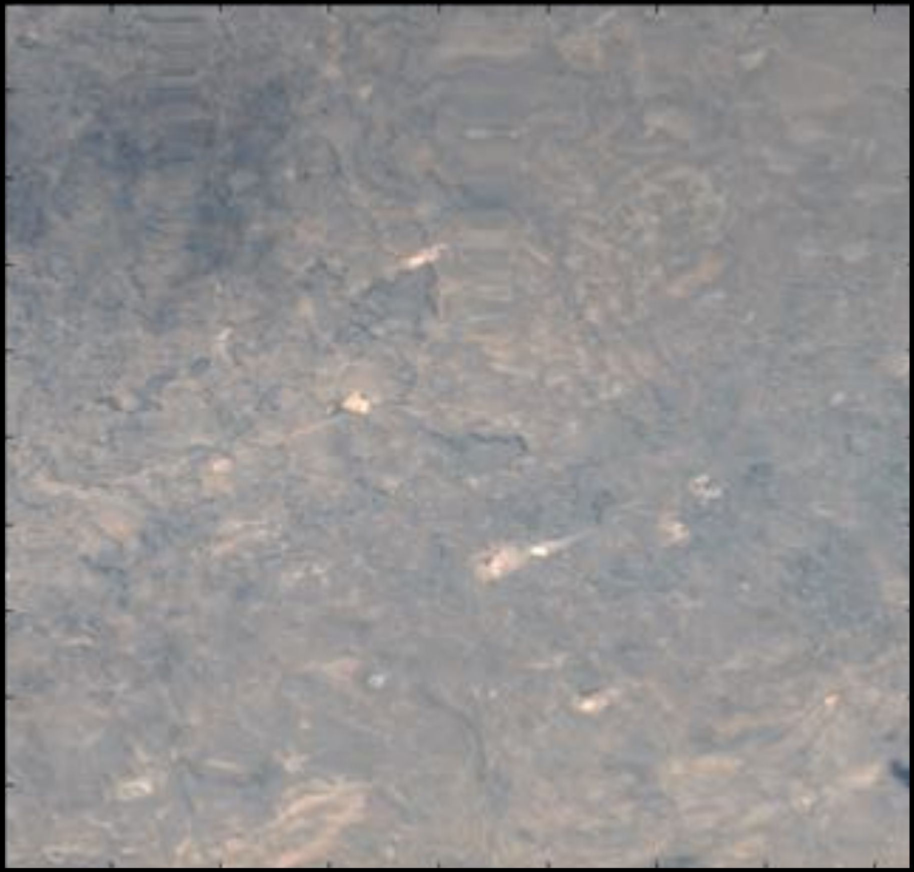


Ground scan (13:25:30)

R = 653 nm, G = 535 nm, B = 457 nm

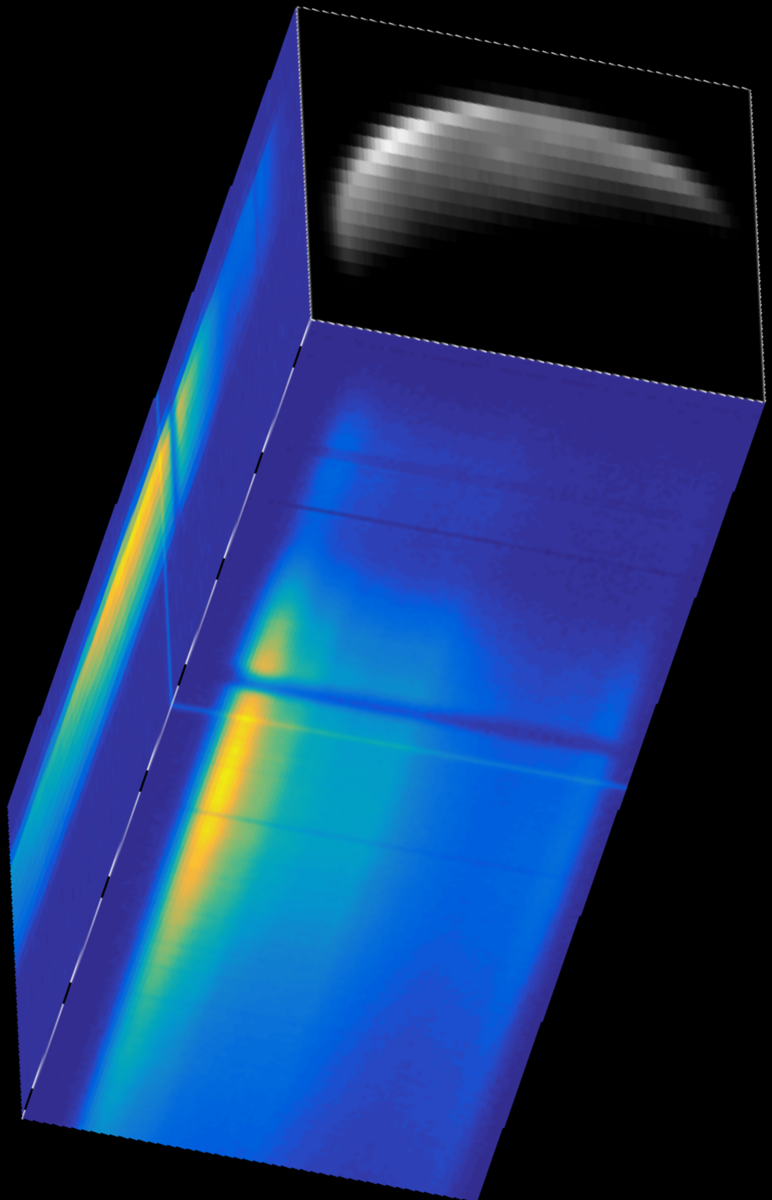
HySICS Ground Scans from Flight #2

- Each Flight #2 ground scan acquired in ~5 min. from 4200 images



Earth Limb Scans Acquired from HySICS

Lunar Data Cube from HySICS Flight #2



HySICS Cross-Calibration Formalism

Spatial/spectral ground-images, $S_{\mathrm{meas\_obj}}(\lambda)$ [DNs], are converted to physical spectral-irradiance units [W m^{-2} nm^{-1}] by an on-orbit-determined unit-conversion factor, $C(\lambda)$ [W m^{-2} nm^{-1} DN^{-1}], and the radiance-attenuation factor, $A(\lambda)$ [unitless], which corrects for the optical-throughput and integration-times used for solar- vs. Earth-viewing

$$\boxed{S_{\mathrm{SI}}(\lambda) = S_{\mathrm{meas\_obj}}(\lambda)\, A(\lambda)\, C(\lambda)}$$

where $S_{\mathrm{SI}}(\lambda)$ represents the radiance of the observed scene in SI-traceable, physical units and $C(\lambda)$ is the unit-conversion factor

$$\boxed{C(\lambda) = SSI(\lambda) \,/\, S_{\mathrm{meas\_Sun}}(\lambda)}$$

with $SSI(\lambda)$ being the SSI (provided by an independent space-flight instrument or a solar model) and $S_{\mathrm{meas\_Sun}}(\lambda)$ the HySICS's in-flight measurement of the SSI in DNs acquired by spatially-integrated cross-slit scans of the solar disk.

HySICS Cross-Calibration Formalism

Being a measurement of ratios acquired over a short period of time, the HySICS solar cross-calibration approach does not rely on intrinsic calibration accuracies or long-term stability

$$S_{\mathrm{SI}}(\lambda) = SSI(\lambda) \cdot S_{\mathrm{meas\_obj}}(\lambda) \, / \, S_{\mathrm{meas\_Sun}}(\lambda) \cdot A(\lambda)$$

All following uncertainties are k=1 unless otherwise noted

FPA Corrections & Uncertainties

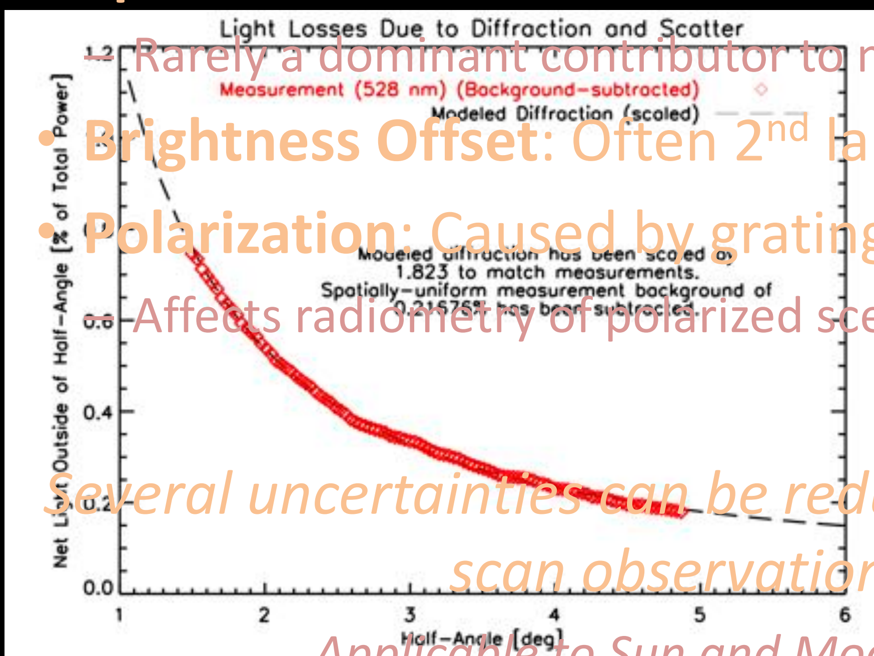
- **Bad-Pixel** removal
- **Read Noise**: determined for each pixel; 8.3 DN average
- **Dark Signal**: 0.29 DN for longest integration times (negligible)
- **Thermal Background**: scene- and temperature-dependent
  - Can also contribute to shot noise
- **Linearity**: ~0.30%±0.12%
- **Gain**: determined for each pixel; 12.01±0.12 e^-/DN average
  - <0.003% of a 15% full-scale signal
- **Flat-Field**: Acquired on-orbit by solar and lunar scans

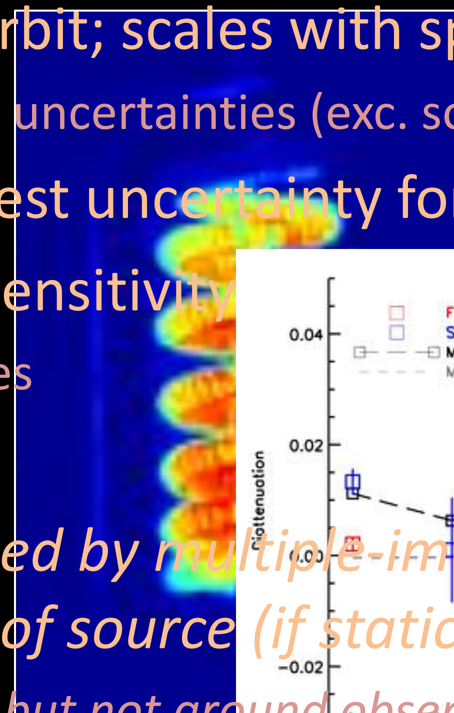
Several uncertainties can be reduced by multiple-image or repeated-scan observations of source (if static)

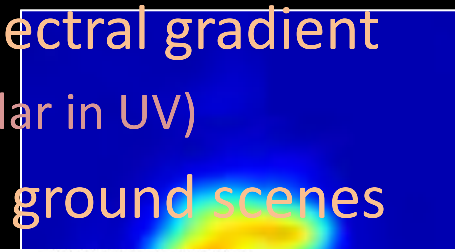
Applicable to Sun and Moon but not ground observations

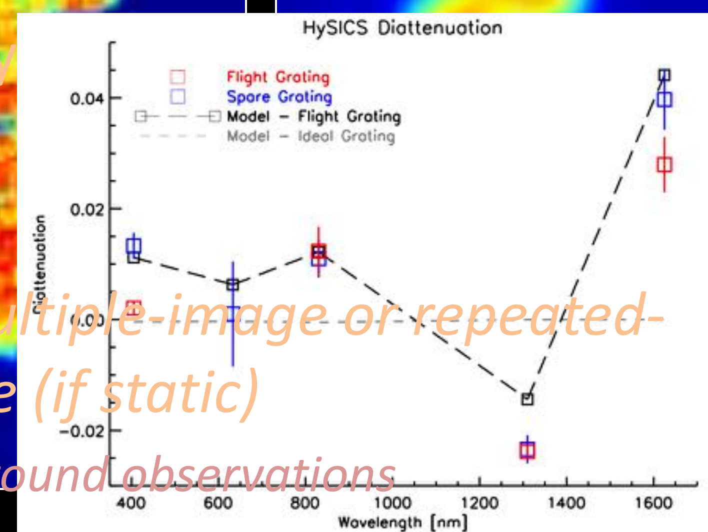
Instrument-Level Uncertainties

- **Shot Noise**: signal-dependent; dominant source of uncertainties for ground scenes across much of spectrum
- **Diffraction & Scatter**: measured and modeled; affects solar observations at long wavelengths
  - Using NIST-quoted 10% uncertainties
- **Spectral Scale**: Determined on-orbit; scales with spectral gradient
  - Rarely a dominant contributor to net uncertainties (exc. solar in UV)
- **Brightness Offset**: Often 2nd largest uncertainty for ground scenes
- **Polarization**: Caused by grating sensitivity
  - Affects radiometry of polarized scenes









Several uncertainties can be reduced by multiple-image or repeated-scan observations of source (if static)

Applicable to Sun and Moon but not ground observations

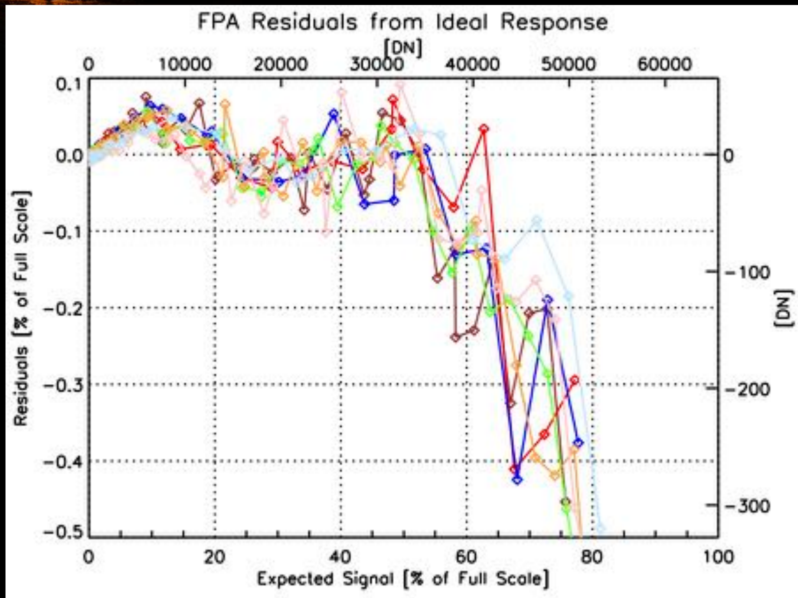
Measurement Uncertainties

$$S_{\mathrm{SI}}(\lambda) = SSI(\lambda) \cdot S_{\mathrm{meas\_obj}}(\lambda) / S_{\mathrm{meas\_Sun}}(\lambda) \cdot A(\lambda)$$

ground solar aperture

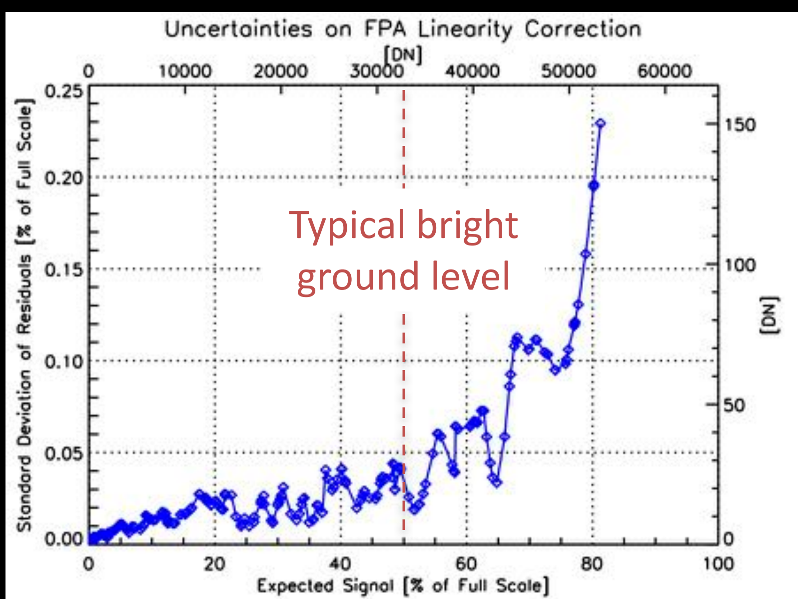
see Kopp et al. 2017 for final uncertainties

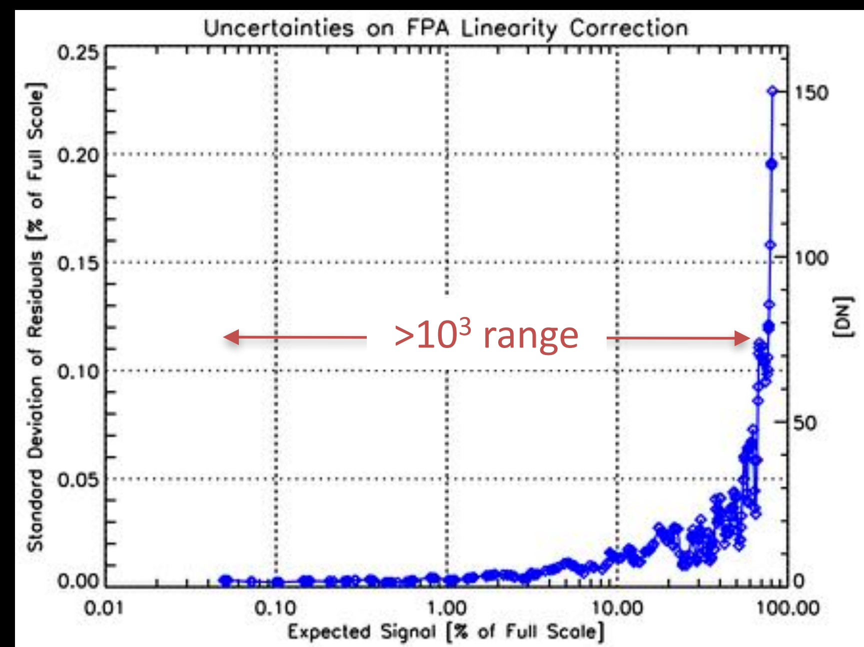
Attenuation Uncertainties – Integration Time



Method provides greater attenuation range with lower uncertainties than anticipated, contributing little to attenuation uncertainties

Uncertainty Parameter	Bright Scene (53% FS) [%]	Max. Int. (75% FS) [%]
Electronic Linearity	0.00016	0.00016
Gain Non-linearity	0.050	0.120
Total	**0.050**	**0.120**



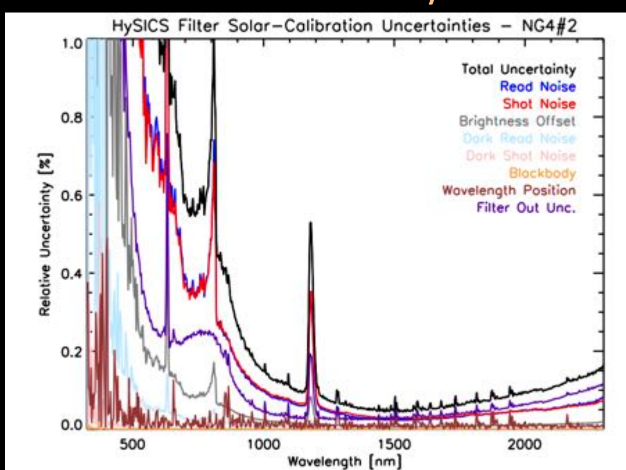


Attenuation Uncertainties – Filter Ratio (Sun)

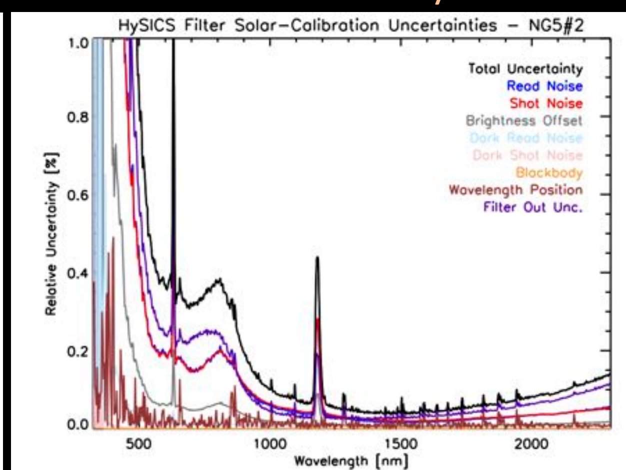
- Filter calibration uncertainties 0.04% - 0.1% from 1000 - 2300 nm
  - Dominated by read- and shot-noise, especially in the UV/Visible region

Parameter	Measurement Uncertainty (%)			Measurement Uncertainty (%)			Measurement Uncertainty (%)		
	550 nm	1000 nm	2000 nm	550 nm	1000 nm	2000 nm	550 nm	1000 nm	2000 nm
Filter (Solar Calibration)	**NG4#2**			**NG5#2**			**BG25**		
Shot Noise	0.94	0.1	0.047	0.25	0.065	0.035	NA	0.027	0.018
Read Noise	0.97	0.097	0.048	0.25	0.06	0.035	NA	0.015	0.011
Wavelength Bin Location	0.027	0.015	0.009	0.027	0.015	0.009	0.027	0.015	0.009
Filter-out Uncertainty	0.35	0.049	0.064	0.35	0.049	0.064	0.35	0.049	0.064
Background Level Correction	0.23	0.023	0.011	0.082	0.02	0.011	NA	0.005	0.003
Blackbody Radiation Correction	0.0001	0	0	0	0	0	NA	0	0
Dark Image Read Noise	0.069	0.007	0.003	0.018	0.004	0.002	NA	0.001	0.0008
Dark Image Shot Noise	0.003	0.0003	0.0001	0.0007	0.0002	0	NA	0	0
Total	**1.416**	**0.150**	**0.094**	**0.505**	**0.104**	**0.082**	**NA**	**0.060**	**0.068**

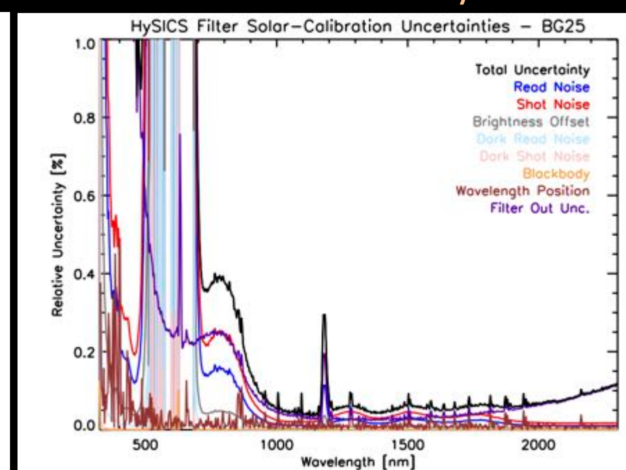
Filter Ratio Uncertainty: NG4 #2



Filter Ratio Uncertainty: NG5 #2

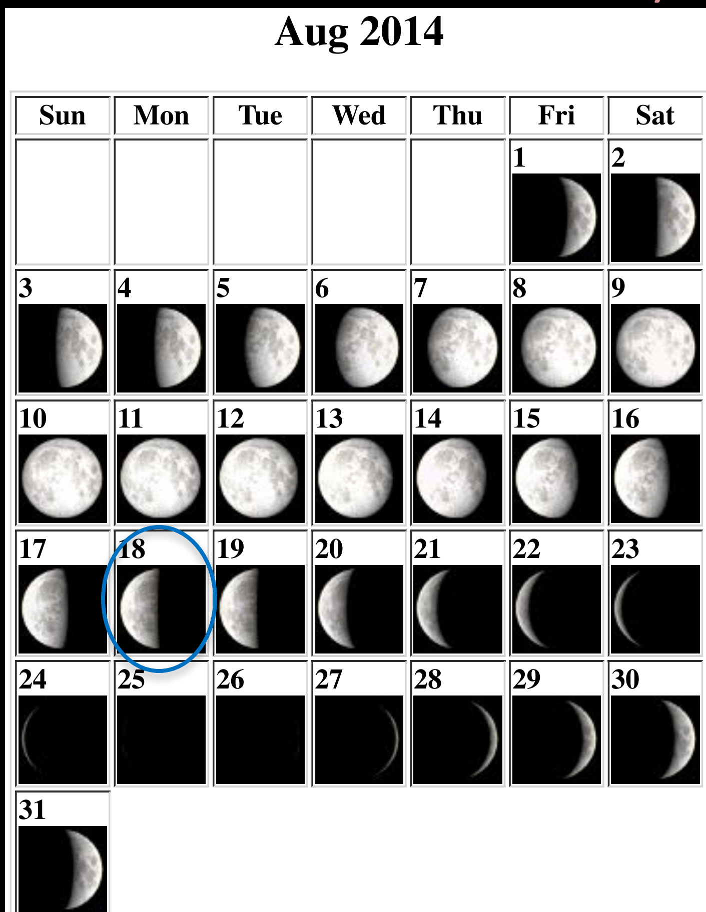


Filter Ratio Uncertainty: BG25

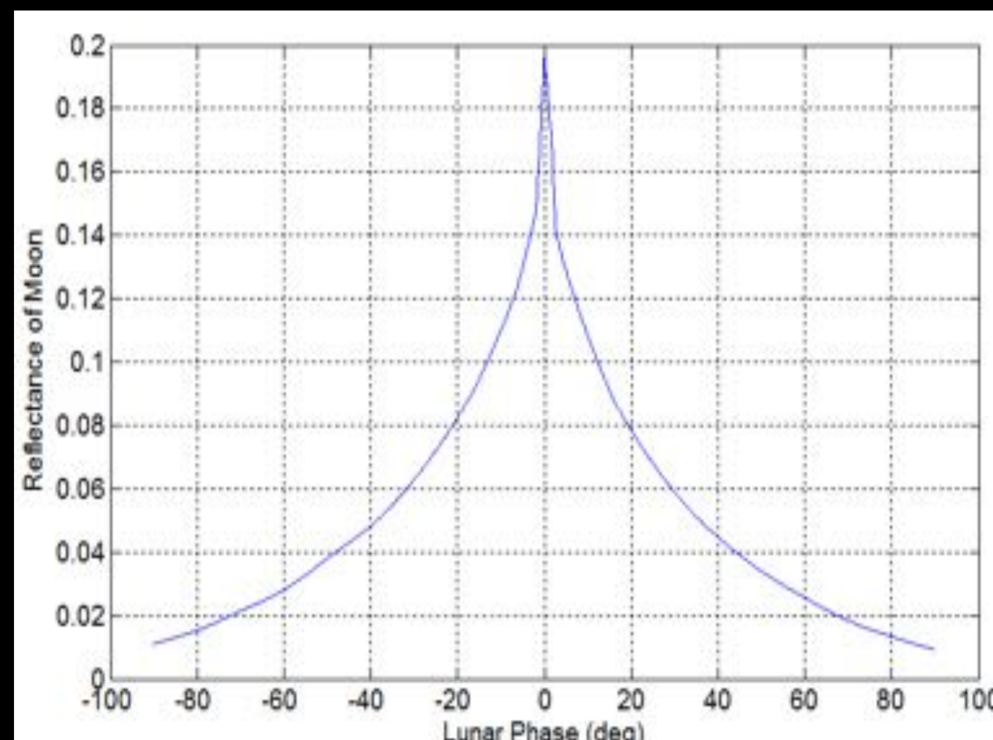


Lunar Calibrations Limited at Time of Flight

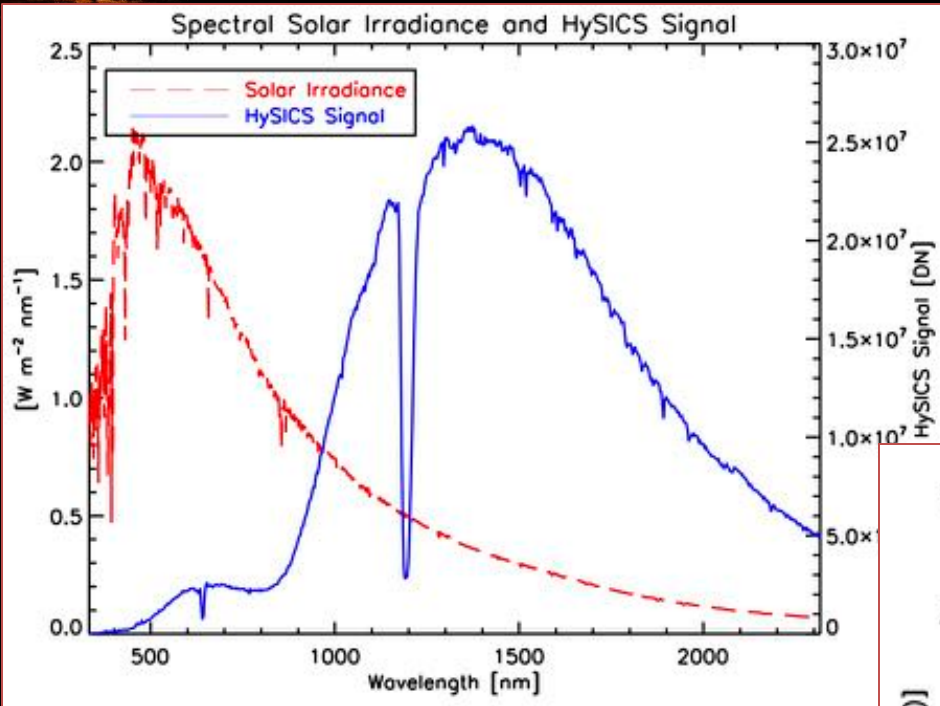
- Filter calibrations and flat-fielding from Moon of limited success
  - Limited by the low lunar signal from the narrow lunar crescent and pointing sensitivity
  - Lunar filter ratio uncertainty 1% - 2% from 600 - 2300 nm



Lunar Phase >90°



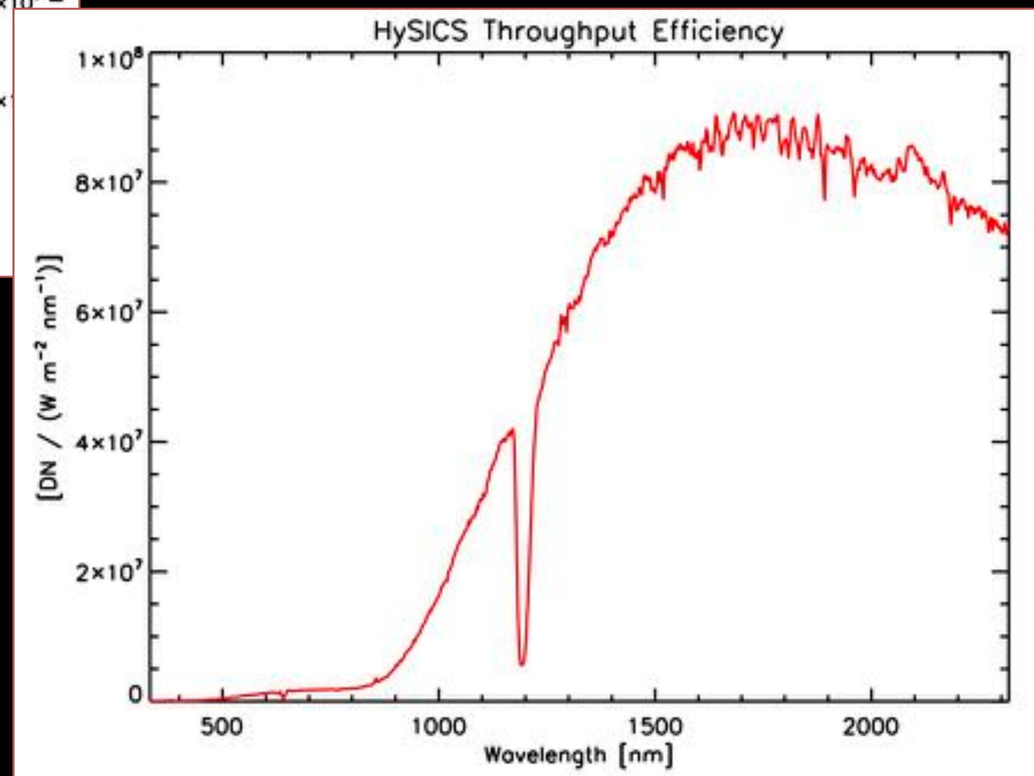
HySICS Efficiencies Characterized On-Orbit



On-orbit SI-calibration obviates need to transfer ground calibration to space

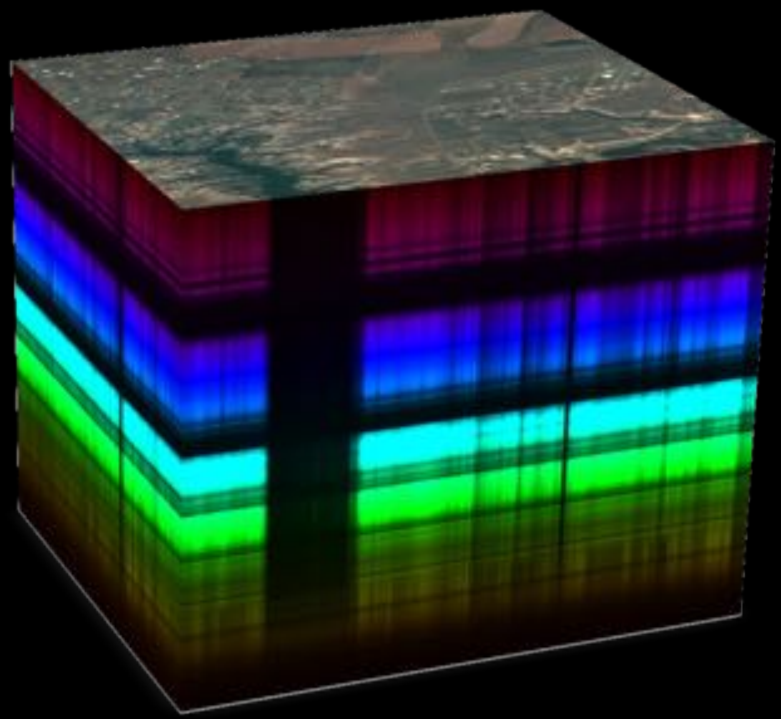
This is the whole purpose of the solar cross-calibration approach

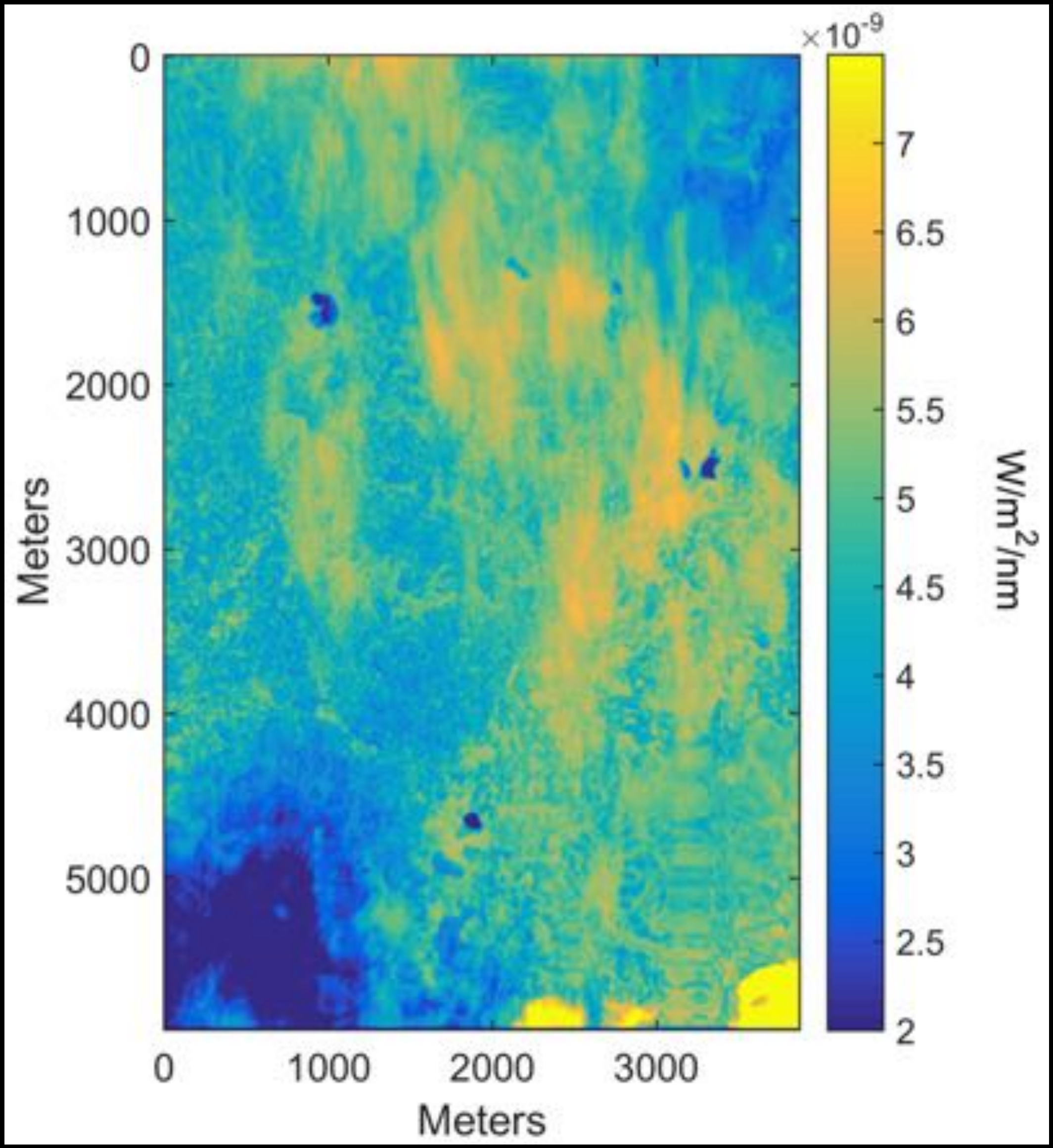
On-orbit calibrations come from measurements of ratios, so **accuracy does not rely on absolute calibrations or on long-term stability**



End Result – Radiometric Ground Image

- Applying spectral solar irradiance calibrations to the HySICS data enables radiometrically-calibrated data cubes





HySICS References

- G. Kopp, P. Smith, C. Belting, Z. Castleman, G. Drake, J. Espejo, K. Heuerman, J. Lanzi, and D. Stuchlik, "Radiometric flight results from the HyperSpectral Imager for Climate Science (HySICS)," *Geoscientific Instrumentation*, 2017, in press
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HySICS Accomplishments Summary

- Designed, built, and tested a hyperspectral imager for Earth viewing
- Demonstrated flight solar cross-calibration technique and quantified spectrally-dependent uncertainties for 3 attenuation methods via two high-altitude balloon flights
  - Aperture area ratios $10^{-3.2}$, integration timing 10^{-3}, filters $10^{-0.9}$
  - Net attenuations of $10^{-7.1}$ exceed IIP's $10^{-4.7}$ goal
  - Filter attenuation method not needed for spaceflight instrument, saving mass and complexity
- Demonstrated ~2x improvement in radiometric accuracies *in flight*
  - Instrument and calibration changes expected to provide another ~2x improvement
- Applied SI-traceable radiometric scale to measured radiances
- Demonstrated single focal-plane-array spectrometer spans desired wavelengths
  - Reduces mass, volume, power, and cost for spaceflight instrument
- Improved ground-based test facility for calibrations of solar attenuator system and quantifications of uncertainties

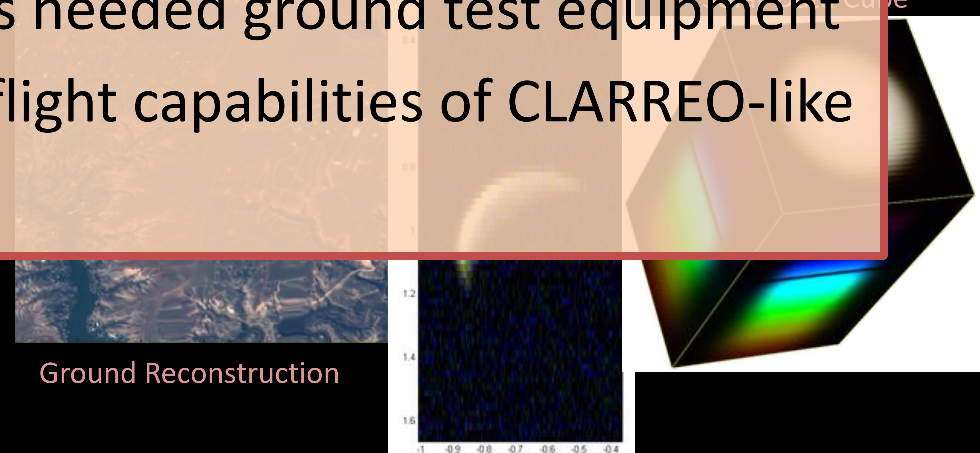
Elevated TRL from 3 to 6

HySICS

PI: Greg Kopp / LASP

- HySICS demonstrates improved radiometric accuracies based on solar cross-calibrations under realistic <u>flight</u> conditions
- HySICS acquired representative 350-2300 nm spatial/spectral data of the Sun, Moon, and Earth
- HySICS demonstrates the feasibility of acquiring reflected solar data with a single spectrometer
  - Reduces mass, power, volume, cost, risk, and complexity
- HySICS builds on and improves needed ground test equipment
- HySICS demonstrates several flight capabilities of CLARREO-like reflected solar instrument

WFF demonstrate on-orbit capabilities



Ground Reconstruction

CoIs: Co-I – Peter Pilewskie / LASP
Balloon Flight Manager – David Stuchlik / WFF

HySICS' View of Instrument Team

Thank

you!